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Sustainable Urban Farming Rack Design Using Eco Friendly Materials with Variety Load

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Abstract

Vertical farming requires a structurally sound and environmentally sustainable racking system; however, existing research largely neglects the evaluation of the structural safety of eco-friendly racking materials under various operational loads. This gap necessitates further rigorous mechanical performance assessments to ensure the long-term reliability of the system. This study aims to develop a vertical farming racking design with an adequate safety factor by examining its structural response to various load scenarios. A design-construction methodology supported by SolidWorks simulations was used to evaluate stress distribution, strain behavior, and deformation patterns. Simulation results using SolidWorks software indicate that the maximum compressive stress at the loaded joint surface is 13.734 MPa, while the minimum stress is 1.149 MPa. The highest load occurs at the fourth (bottom) joint level due to pump-induced water pressure. The maximum strain recorded is 0.00491, with a minimum of 0.00041. The top shelf level exhibits a maximum displacement of 48.165 mm, while the minimum displacement is 0 mm. This shows that the material and shape of the frame that has been made are in the safe category with a safety factor (sf) of 2.4. These findings indicate that the proposed rack design maintains structural integrity within safe limits and is suitable for application in vertical farming systems.

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1. Introduction

Various elements that support vertical farming make it an attractive option for city dwellers, considering that urban areas experience difficulties regarding food security, while vertical farming can strengthen food security (Mustafa & Sena, 2024; Rafiuddin & Khursatul Munibah, 2016; Yeremia & Carina, 2022). Land conversion, a phenomenon encountered today, has led to a decline in the availability of agricultural land (Erfiana et al., 2025). Rapid population growth is expected to lead to the global population reaching 8.9 billion by 2050. In order to sustain such population growth, global

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food production must grow more than 70% by 2050. VF utilizes stacked levels of growing racks and beds to maximize the growth space per square foot of land and typically uses hydroponics to reduce water use (Zhang et al., 2020).

Vertical farming is the practice of producing food and medicine in stacked vertical layers, on vertically inclined surfaces, and/or integrating them into other structures (Mustafa & Sena, 2024). The best solution to address land constraints due to the ever-increasing population is vertical development. Several factors support vertical farming as a choice for urban communities because urban areas face challenges in food security, and vertical farming can improve household food security in these areas (Kusumo et al., 2020; Subagyo et al., 2022). A vertical farming system can be implemented by constructing tiered plant racks, a cross-stacked model with varying numbers of rack levels, resulting in a larger plant. This cross-stacked model is arranged such that the shading effect of the upper racks on the lower racks of each row of plants is reduced (Zhang et al., 2020; Mustafa & Sena, 2024; Rahmat et al., 2025; Harani, 2022).

Vertical growing racks are tiered shelving units designed to support plants and their growth media in compact spaces (Pandapotan, 2022). Urban farming emerged from the desire of urban communities to continue farming, even on limited land (Riska, 2024). Conventional farming requires large areas to support human food needs (Riska, 2024). Furthermore, this system can be integrated with hydroponics, aeroponics, or traditional soil-based gardening techniques, offering great flexibility (Eddy et al., 2019; Rafiuddin & Munibah, 2016) (Darius & Purnama, 2020). The main components of a vertical gardening system include study shelves, grow lights, irrigation systems, and ventilation. Unlike traditional horizontal gardening methods, vertical gardening ensures that each level receives adequate light and nutrients, thereby optimizing plant health and growth rates. To address this issue, hydroponic farming has been developed as a substitute for rice paddy farming. Hydroponics is a method of growing plants without using soil as a medium. Hydroponics literally means growing in water containing a nutrient solution (Wali et al., 2021; Fadli et al., 2020; Syidiq, 2022). Plants have different characteristics, so not all plants can be cultivated hydroponically. There are many types of hydroponics, including the wick system, nutrient film technique, deep water culture (DWC), drip system, and ebb-and-flow system (flood-and-drain system). Hydroponic farming is currently an alternative to overcome land limitations (Saroinsong, 2022). Hydroponics can be implemented using various techniques, one of which is a simple technique using a wick system, utilizing used mineral water bottles and rice husk charcoal as a growing medium (Utami et al., 2020).

Storage is the activity of storing, arranging, or storing (storage) to facilitate the retrieval. Furthermore, the wide variety of sizes available makes storage facilities ineffective and inefficient, leading to activity disruptions (Lerman et al., 2022; Lubis et al., 2025). This is due to the inability of furniture design to meet varying functional and size requirements. The relatively lower rental price

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in strategic locations compared to conventional offices or shophouses, along with flexible rental contracts, is also a key factor (Razi et al., 2024).

Developing a modern agricultural system using hydroponics is considered a viable alternative because it does not require extensive land use (Riska, 2024). Therefore, modern agriculture using hydroponics can continue to be developed to open new businesses, and the resulting products can be used for personal consumption and marketed for profit. Water culture hydroponics was used to implement hydroponic farming. Plants were grown in a medium using a solution. Vertical farming can be monitored using this research, where the vertical farming water reservoir is installed with several sensors to collect data, so that there is no need to be directly on the farm to check (Ekawati et al., 2025). The material of the hydroponic rack frame was adjusted based on the required load. An analysis of the rack strength will be conducted using ivory pipe material to obtain a more efficient and economical frame and ease of assembly (Rahmat et al., 2025). The compact rack design uses a simple system that is easy to assemble and disassemble and suits the interior of the house (Sadida & Pratama, 2024). The results show that hydroponic racks with a modular system are suitable for small and compact condominium and apartment areas, and the selection of appropriate materials and precision in design are important. The research objective is to create a vertical rack model that will later be used for a pilot project and as a pilot that combines sturdy vertical racks using environmentally friendly materials.

2. Material and Methods

2.1 Material

One of the most critical components of a vertical farming system is the plant rack, which supports the growing medium, including planting bags, water, and the plants themselves. Therefore, the rack must be designed to be sufficiently strong to support the weight of the plants, water, and other equipment. This ensures that as the plants grow larger, there will be no deformation of the rack, which could cause damage to the plants. The material used in this work was a polymer cylindrical pipe of thermoplastic Acrylonitrile Butadiene Styrene (ABS) with standard dimensions for ivory pipe, an outer diameter (OD) of 28 mm, a wall thickness of 0.8 mm or 1 mm, and a standard length of 4 m with a cross-sectional area of 84.8 mm2. This is based on the availability of ivory pipe material in the market and the compatibility of ABS with a wide variety of materials, which makes it very versatile and light. They are a family of copolymers used for technical purposes because of their high physical and chemical properties, such as rigidity, impact resistance, heat resistance, surface appearance, and resistance to many chemical agents (Mirasadi et al., 2024). With its relatively low production cost, this device has the potential for widespread replication and distribution, supporting equitable access to modern agricultural developments and encouraging the adoption of appropriate technologies in agriculture (Pai et al., 2022).

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Polymer materials are widely used in various industries. They are readily available and used in various applications. These materials play a crucial role because of their diverse functions and widespread use by manufacturers (Ali et al., 2022). Many manufacturing industries already utilize polymers in various products, such as material racks, trolleys, and conveyors. ABS Material are frequently used in various sectors, particularly when impact-resistant materials, attractive appearance, and environmentally friendly design are required owing to ABS's recyclability (Jeswani et al., 2021). This material is preferred for making household appliances, vehicle interiors and hospital X-ray platforms. ABS belongs to the styrenics family of polymers (Czyżewski et al., 2024). It is a copolymer of acrylonitrile, butadiene, and styrene, which was first discovered in the United States in 1946. ABS consists of three monomers: acrylonitrile, butadiene, and styrene (styrene). This material is produced by modifying a copolymer resin (styrene-acrylonitrile) with a copolymer (butadiene-acrylonitrile).

Table 1. The Mechanical Properties of ABS (Ali et al., 2022)

Elongation at Break	10-50%
Elongation at Yield	1.7-6%
Flexibility (Flexural Modulus)	1.6-2.4 GPa
Hardness Shore D	100
Strength at Break (Tensile)	22.1-74 MPa
Strength at Yield (Tensile)	13-65 MPa
Toughness (Notched-Izod Impact at Room Temperature)	8-48 KJ/m^2
Toughness at Low Temperature (Notched-Izod Impact at Low Temperature)	7-22 KJ/m^2
Young's Modulus	1.79-3.2 GPa

The next stages are modeling the rack structure, test simulation, determining the design, making racks, and analyzing the rack structure. Of the five research journals, there are similarities; namely, two studies both use qualitative research methods and discuss the design of vertical farming racks. Meanwhile, in the vertical rack design process, a cross-stack model was developed, which was arranged such that the shading effect of the upper rack on the lower rack of each row of plants was reduced (Rahmat et al., 2025). The differences found between previous studies include the use of environmentally friendly materials, actual loading, and non-destructive testing (Zhang et al., 2020).

2.2 Research Methodology

The research methods used in this study included engineering design, load modeling, finite element analysis (FEA), and SolidWorks simulation. The racks were tested using nondestructive testing (NDT) methods using SolidWorks 3D simulation. The strength analysis included stress,

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deformation, and safety factors at various critical points on the vertical farming rack frame. Actual testing will also be conducted to determine the ability of the rack to withstand the weight of the growing media placed within.

The racks will be placed in a 15-meter-long and 5-meter-wide area prepared by the campus. This area accommodates 14 plant racks of the same size. The plants used will be mustard greens, bok choy, basil and watercress. The spacing between plants will be 150 mm, with five planting holes per planting media pipe. This spacing is expected to ensure even sunlight absorption across all plants grown in the field. The manual fertigation method was carried out simultaneously with irrigation water directly to the plants using an irrigation system, with mixing and administration carried out manually, without timer or sensor automation, because it is still on a small scale.

2.3 Safety Factor Base on Yield Stress

Based on a book, The Safety Factor (sf) is a safety measure designed to make a product, system, or structure safe (Khurmi; & Gupta, 2009). The higher the number of sf, the safer the product or structure. An sf of 1 indicates that a structure or component will fail immediately when the design load is reached and cannot support any additional load. Structures or components with sf less than one are not acceptable. If the consequences of failure are severe, such as loss of life or physical injury, a higher sf will be required, either by design or by law. The Safety Factor (sf) based on the yield stress is expressed as follows:

a. sf = 1.25 – 1.5: controlled conditions, and the working stress can be determined with certainty.
b. sf = 1.5 – 2.0: known material with constant load and stress conditions that can be easily determined.
c. sf = 2.0 – 2.5: Material that operates at an average rate with known load limits.
d. sf = 2.5 – 3.0: known material without testing. Under average load and stress conditions.
e. sf = 3.0 – 4.5: known material. Uncertain loads, stress, and environmental conditions.
f. Repetitive Loads: Numbers 1 to 5
g. Shock Loads: Numbers 3 – 5
h. Brittle Materials: Numbers 2 – 5 multiplied by 2

The factor of safety varies according to the situation. Systems are intentionally designed to be much stronger than they need to be in normal settings. This increases the likelihood that they will continue to function even under extreme conditions, such as emergency situations, added loads, overuse, or degradation caused by wear and tear.

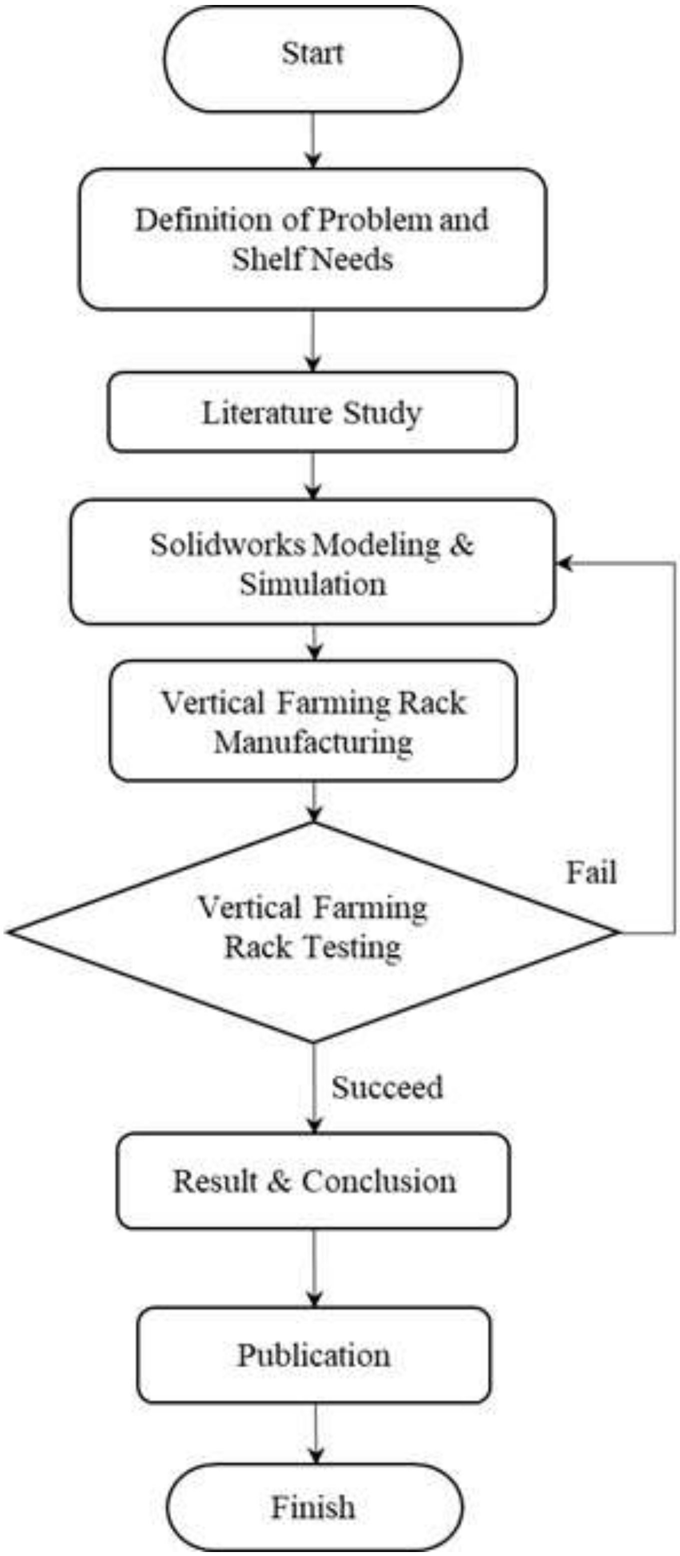

Figure 1. Research Flow Chart.

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3. Results and Discussion

3.1 Vertical Rack Design

Vertical farming is an innovative solution to the modern challenges of agriculture. This method addresses the increasingly pressing land constraints and rising population growth, particularly in urban areas. By adopting high-tech systems, such as hydroponics or aeroponics, vertical farming enables indoor crop production while efficiently utilizing space. In this study, the researchers used a vertical farming plant rack design employing aeroponic and hydroponic methods. The design uses thermoplastic polymers, such as ABS materials, which are widely available on the market, although their availability is limited. This material is environmentally friendly and sufficiently durable for use both indoors and outdoors, making it suitable for the desired application.

The rack is made using only ivory cylindrical pipe material, which is widely available in the market and has been widely used in the modern manufacturing industry as a material for making trolleys, raw material racks, conveyors, and others. The standard dimensions for ivory cylindrical pipes sold in the market are an outer diameter (OD) of 28 mm, a wall thickness of 0.8 mm or 1 mm, and a standard length of 4 meters with a cross-sectional area of 84.8 mm². The cylindrical pipe is then coated with ABS polymer with a thickness of 0.8 mm - 1.2 mm. The dimensions of the rack were 1500 mm long, 1000 mm wide, and 2000 mm high. The material used was a cylindrical pipe with commercially available dimensions. Each pipe connection was secured with special clamps to facilitate installation and connection during assembly. No additional materials were added to the rack structure, except for the brackets for attaching the wheels at the bottom of the rack, which were made of metal plates. The rack design is shown in the image below.

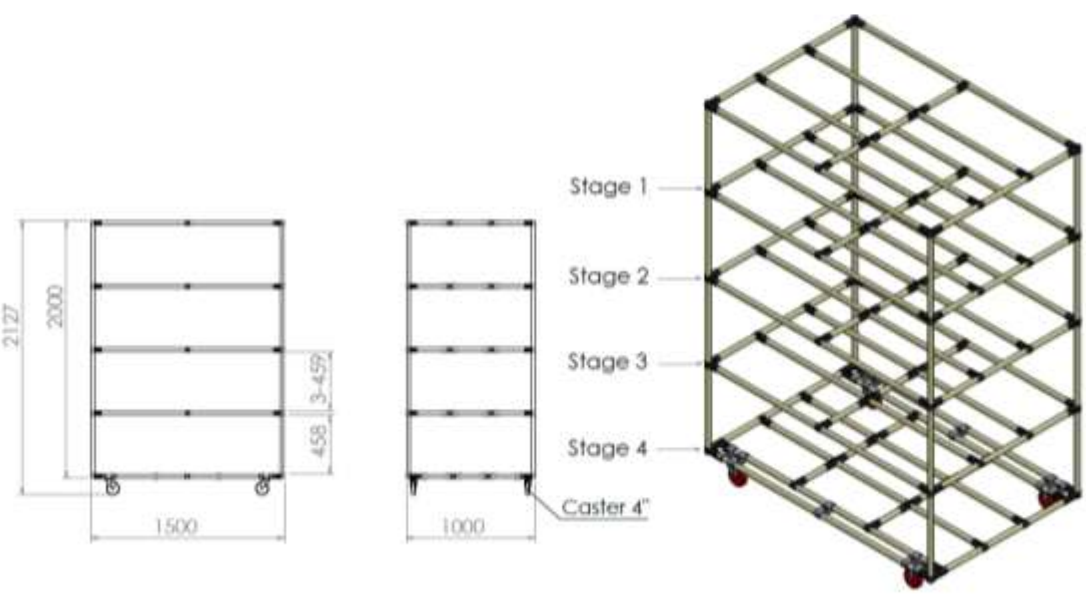

Figure 2. Vertical Farming Rack Design.

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3.2 Structural Strength Analysis of Vertical Farming Rack Design

3.2.1 Stress Analysis

The simulation load is located on four frame legs in the form of caster wheels and is simulated with a load of 30 kg or 300 N for each shelf arrangement, except for the bottom shelf, which uses a load of 10 kg or 100 N, 30 kg or 300 N, and 50 kg or 500 N with the assumption that the bottom shelf receives a larger load because it accommodates a large amount of water circulation. The smallest load simulation was obtained from the assumption that the new tree seedlings were approximately 2 weeks old with a weight of no more than 0.1 kg. The 30 kg simulation load was obtained from the number of trees in the pot, as many as nine trees in each pipe, and the assumption that each pot of each shelf weighs 1 kg and the weight of the circulating water flowing in the pipe is 5 kg in each pipe. The largest load was obtained from the weight of the plant pot during the near-harvest process, which reached 2 kg in each plant pot. Stress is a force that acts on a surface with a unit area. Stress is a scalar quantity with units of $N.m^{-2}$, also known as pascal (Pa). When an object experiences stress, its shape changes.

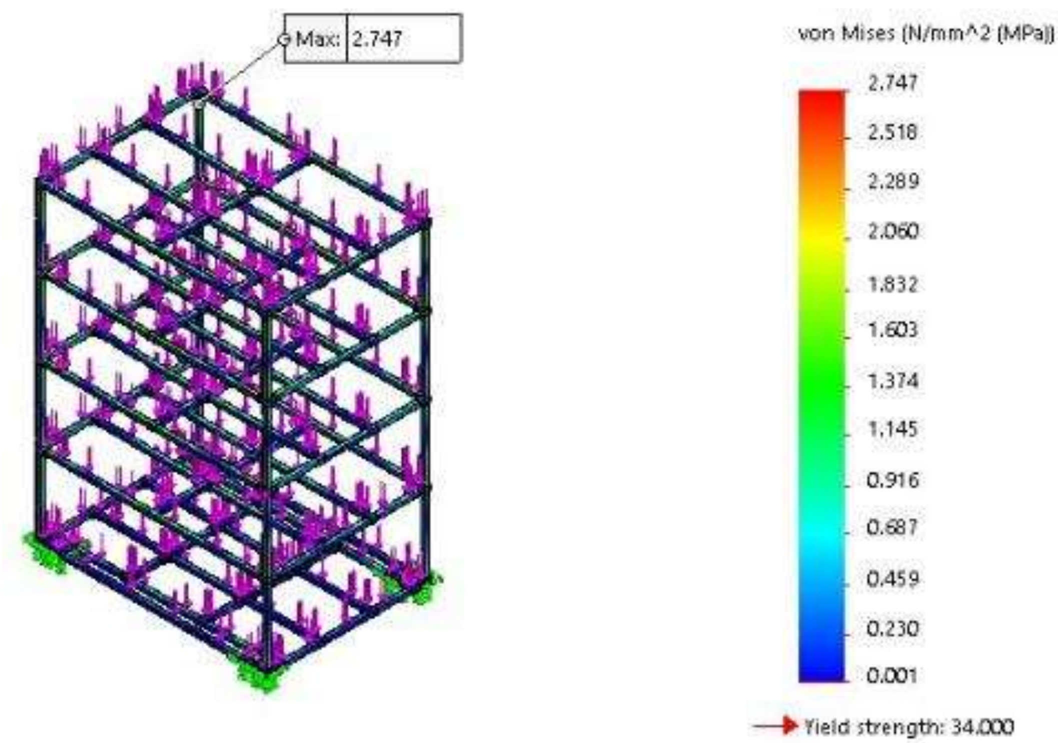

Figure 3. Material Stress Analysis 10 kg.

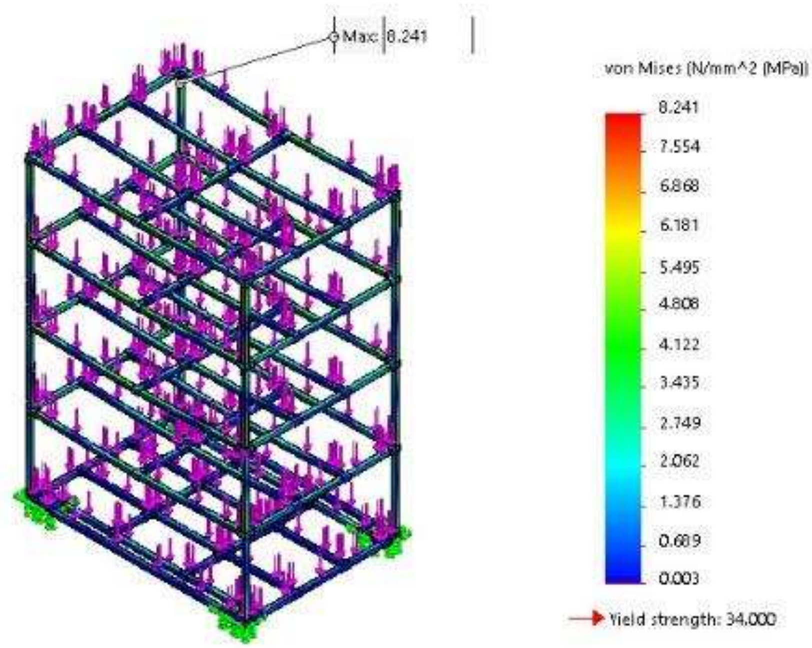

Figure 4. Material Stress Analysis 30 kg.

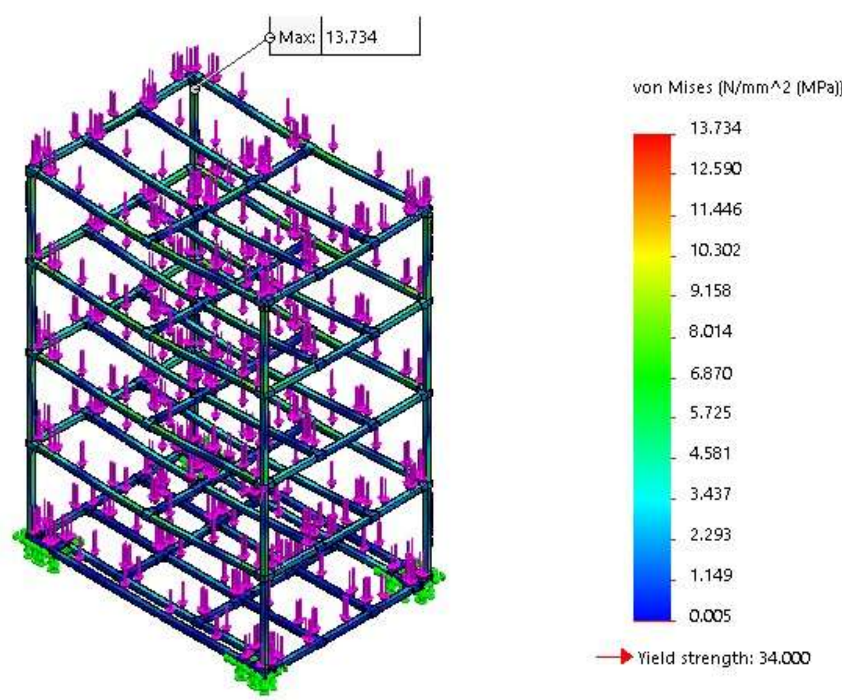

Figure 5. Material Stress Analysis 50 kg.

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From the image of the 4-story rack above, the stress distribution analysis using Solidwork software is shown in red for the maximum stress that occurs at the end of the connection from the surface subjected to the load with a value as shown by the table:

Table 2. Stress Value Simulations

Load (kg)	Max Stress (Mpa)	Min Stress (Mpa)
10	2.747	0.001
30	8.241	0.003
50	13.734	0.005

The greatest load was on the connection at stage no. 4 because this section experienced water pressure from the pump and a heavy load owing to the circulation water tank.

3.2.2 Strain Analysis

Strain is a measure of the deformation or change in the shape of an object owing to the force or stress acting on it. Strain is the ratio of the change in size (length, volume, etc.) of an object to its original size when the object is subjected to stress.

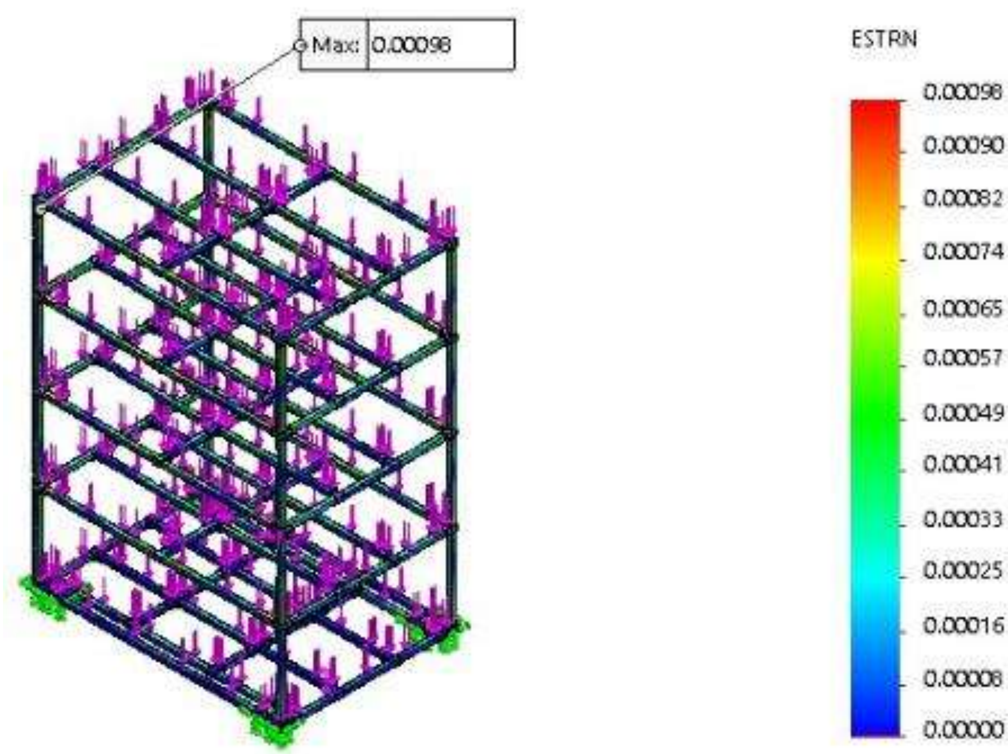

Figure 6. Material Strain Analysis 10 kg.

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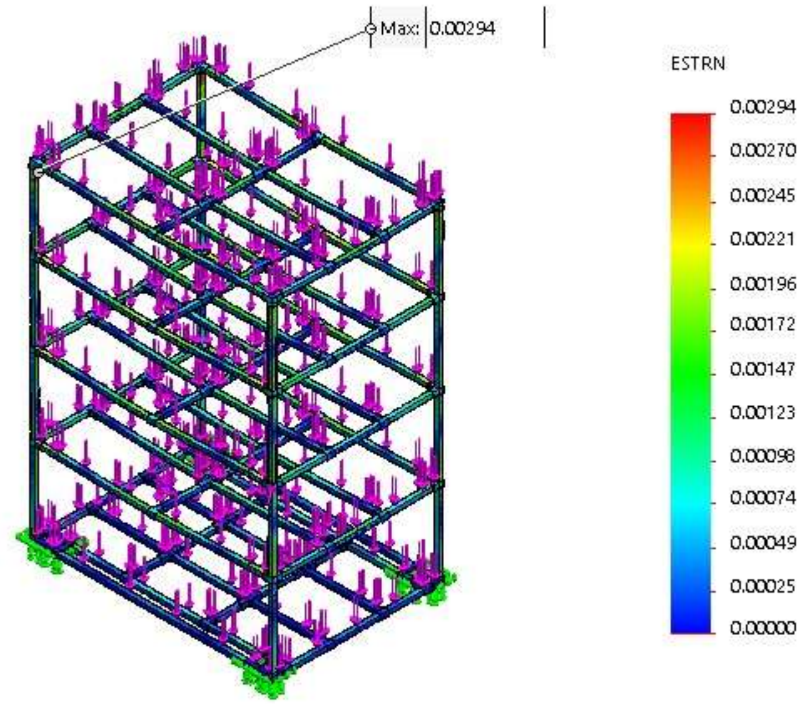

Figure 7. Material Strain Analysis 30 kg.

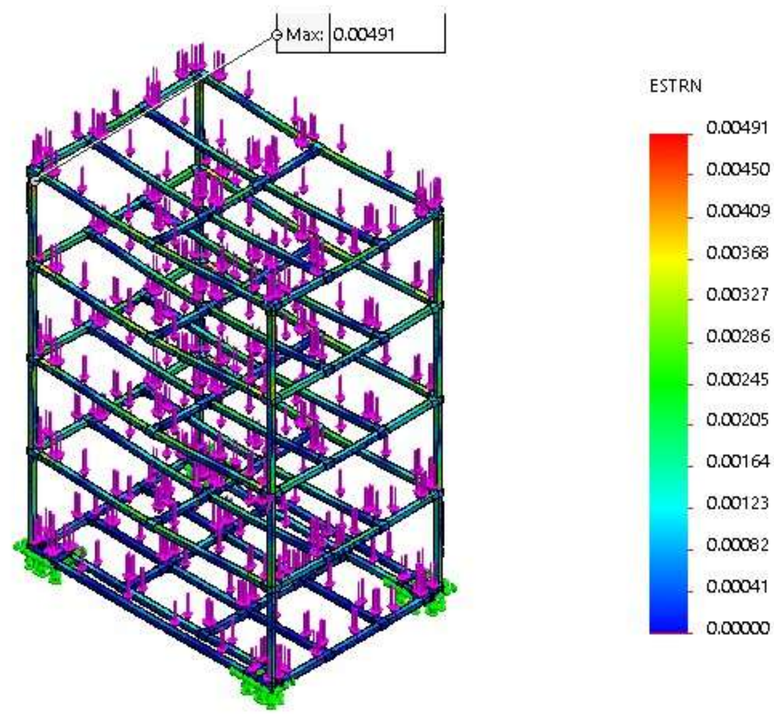

Figure 8. Material Strain Analysis 50 kg.

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From the image of the 1-story rack above, the strain distribution analysis using Solidwork software is shown in red for the maximum stress that occurs at the end of the connection from the surface subjected to the load with a value of 0.00294 while the smallest stress value is 0.00025. The largest load is located at the connection in stage no. 1, where a water tank holding approximately 100 liters of water is located.

Table 3. Strain Value Simulation.

Load (kg)	Max Strain	Min Strain
10	0.00098	0.00008
30	0.00294	0.00025
50	0.00491	0.00041

3.2.3 Displacment Analysis

Displacement is the movement of material from the starting point to the end point, which has been subjected to pressure or load (force) from the pressing process or direct contact.

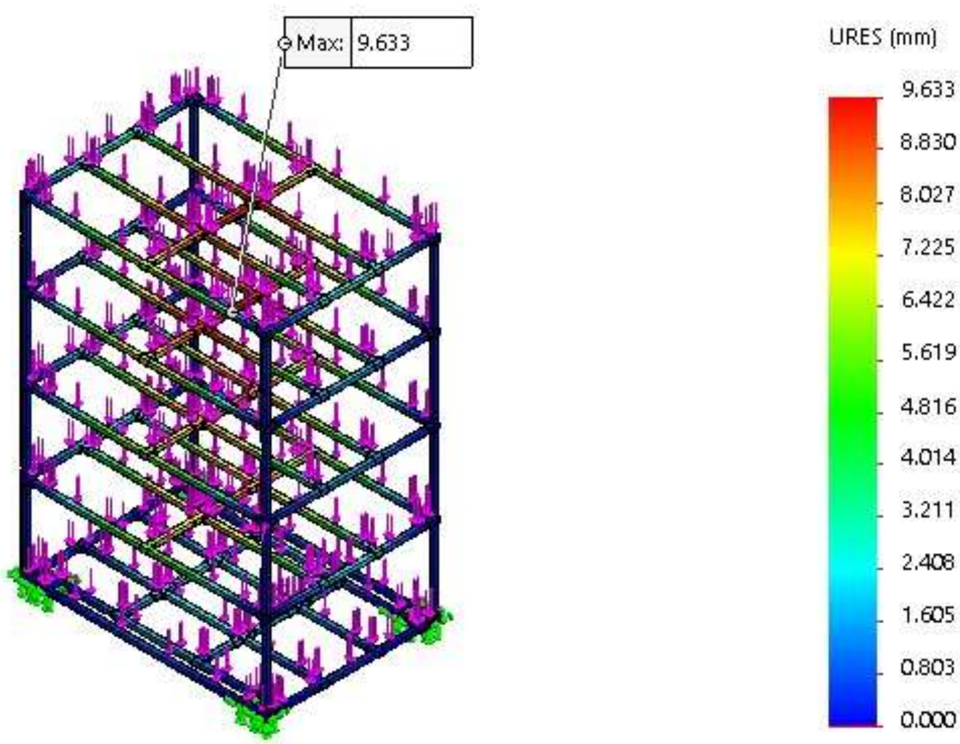

Figure 9. Displacement Analysis for 10 kg.

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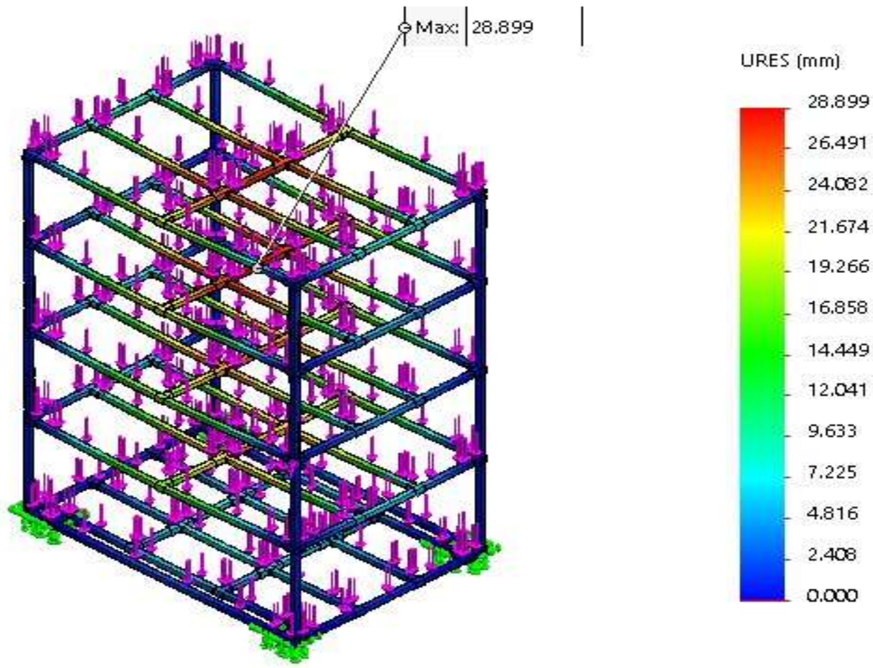

Figure 10. Displacement Analysis for 30 kg.

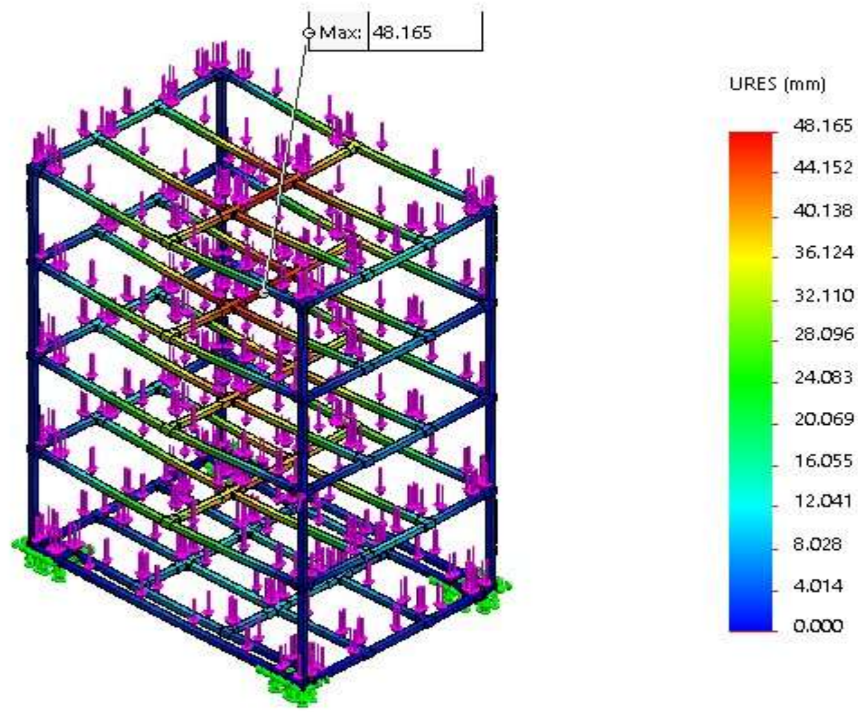

Figure 11. Displacement Analysis for 50 kg.

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The analysis results for the floor rack above show the maximum change (displacement) resulting in deformation, indicated by a value of 48.165 mm (light deformation) in red, and the minimum change, indicated by a value of 0 mm (blue). The resulting displacement values from the test simulation are shown in table below:

Table 3. Displacement Analysis.

Load (kg)	Displacement (mm)
10	9.633
30	28.899
50	48.165

3.2.4 Safety Factor

Many analyses use a safety factor to verify the safety of an object and to determine its function. By simulating the safety factor, we can determine the safety of the frame under load. After obtaining the results of the stress analysis, we can calculate the safety factor by dividing the yield strength of the material by the stress caused by the applied load.

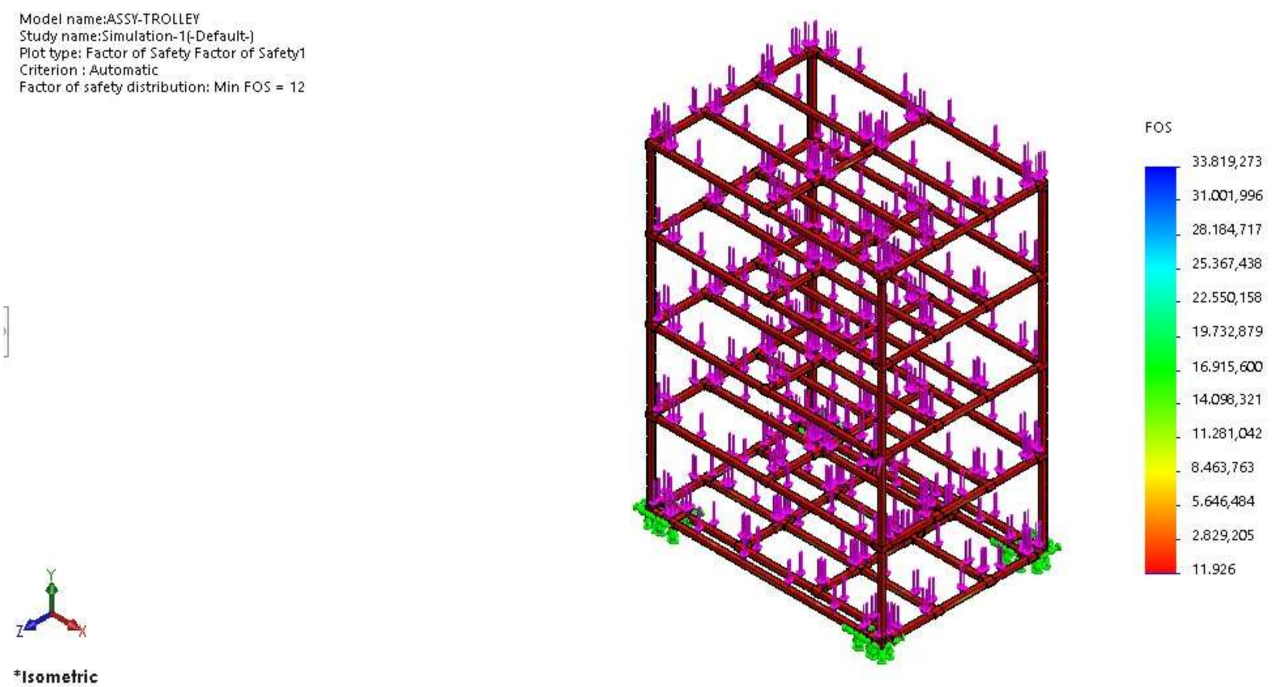

Figure 12. Safety Factor Analysis 10 kg.

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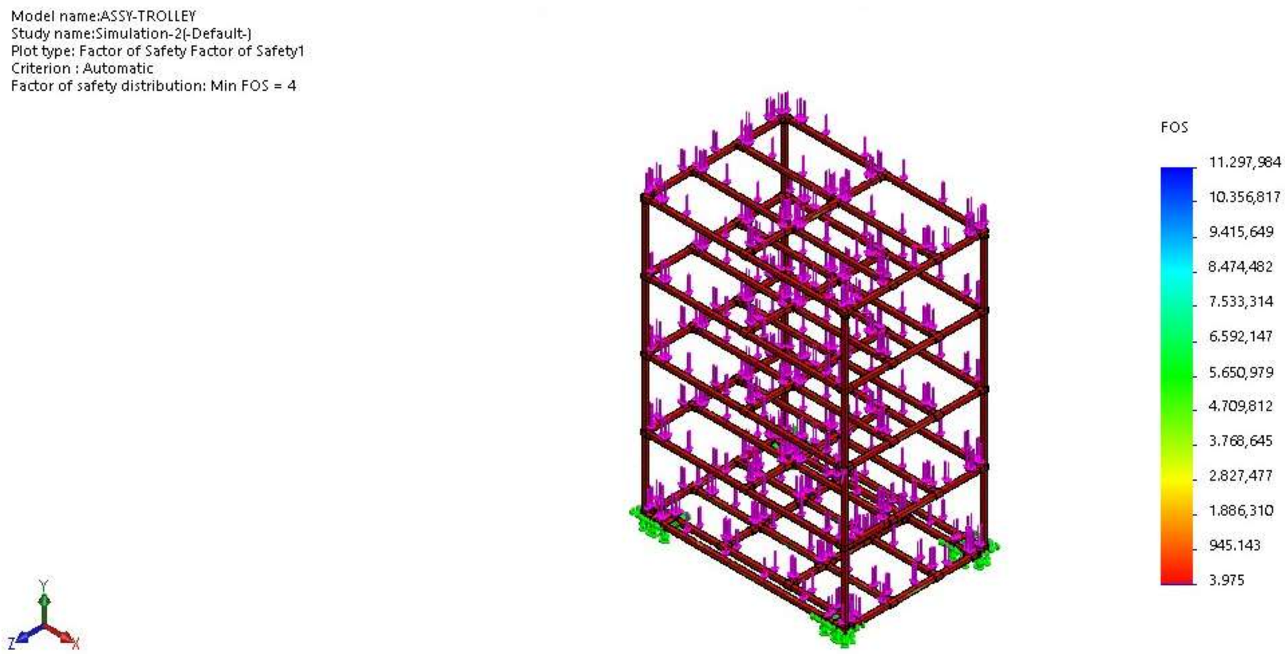

Figure 13. Safety Factor Analysis 30 kg.

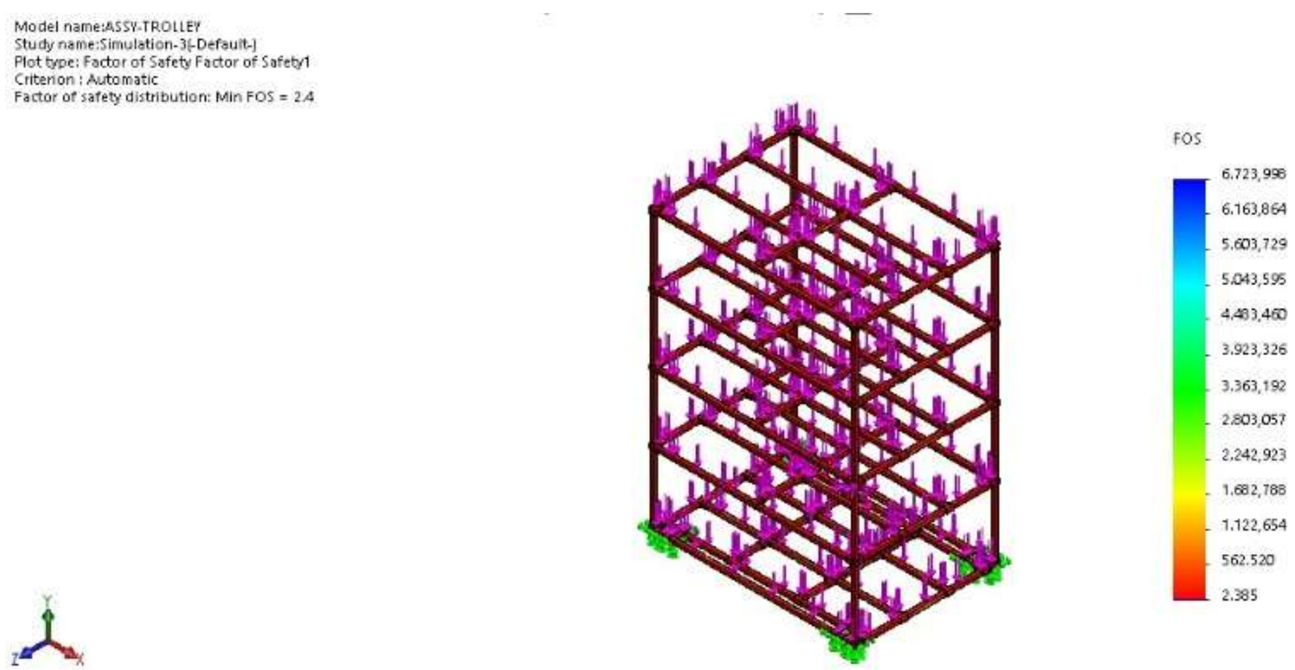

Figure 14. Safety Factor Analysis 50 kg.

The simulation for 3 loads indicated that the ABS material was strong enough to withstand the applied load. The results are shown on the table below.

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Table 4. Safety Factor Analysis.

Load (kg)	Safety factor
10	12
30	4
50	2.4

The results of the simulations showed that the ABS material was sufficiently strong to withstand the applied load and was safe for use as a vertical farming rack.

4. Conclusion

The simulation load is located on four frame legs in the form of caster wheels and is simulated with loads of 10, 30, and 50 kg for each rack arrangement, except for the bottom rack, which uses a load of 100 kg or 1000 N, assuming that the bottom rack receives a greater load because it accommodates large amounts of circulating water. From the simulation results, the maximum compressive strength that occurred at the end of the connection from the surface subjected to the load was 13.734 MPa, while the smallest stress value was 1.149 MPa. The largest load was at connection level 4 because water pressure from the pump was present at that part. The strain distribution analysis for the maximum stress that occurred at the end of the connection from the loaded surface had a value of 0.00491, while the smallest stress value was 0.00041. The largest load was located at connection stage no. 1, where a water tank holding approximately 100 liters of water was present. The results of the analysis on the floor shelf above the maximum change (displacement) resulting in deformation are shown in red with a value of 48.165 mm (slight deformation occurs), and the minimum change is shown in blue with a value of 0. This shows that the material and shape of the frame that has been made are in the safe category with a safety factor (sf) of 2.4.

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